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1 Introduction

The main goal of a testing procedure for solar water heaters is to precisely quantify the system's physical parameters. The test results should enable a reliable prediction of long-term system performance under any set of meteorological and operating conditions. There are numerous additional desirable features of a testing procedure for solar water heaters:

(i) the testing procedure is to be applicable to conventional types of solar water heaters regardless of their design

(ii) within certain limits the identified parameters are to be independent of the testing conditions, so that prediction of long term performance will be possible for various meteorological and operating conditions, as well as for certain modifications of the system installation.

(iii) the test results can be used to trace the sources of system malfunctions

(iv) the procedures for testing and for indentifying parameters are to be simple and inexpensive

Since the requirements of the testing procedure are partially incompatible a decision has to be made on their relative importance and priority.
At present, there is a variety of methods basically different in their approach.

The American standard ASHRAE 95-P [1] is based on a simulation of solar loop performance by means of electrical heater built in to the collector loop.

A method developed by CEC at Ispra [2] and AFNOR [3] is based on a simplified linear correlation model. The system behaviour is characterised by the so called input/output diagram representing useful heat gained by the system versus daily irradiation with the ambient temperature as a parameter. The method is restricted to reasonably designed systems. It has been shown [4] that input/output diagrams could get quite non-linear in intermittent climate conditions and especially for oversized systems typical in central European countries. If that non-linearity is to be properly quantified, the test procedure is to be considerably extended.

A method recently developed at the Technological Institute in Denmark [5] characterises the system components by separate measurements on the components themselves. Although the Danish method is time-consuming and not applicable to ICS systems, it ensures reliable prediction of long-term system performance.

A method presented in this work takes a completely different approach to evaluating and quantifying system design parameters.

The method utilises a daily energy balance equation. On that basis, a closed loop mathematical form is derived most appropriate for identification of system design parameters.

Another feature of the method is that the identification of these parameters is performed by measurements on a complete unit so that interactions between the system components are included.

2 Testing Methodology

The test method presented in this work relies on a daily energy balance equation. Daily energy balance equation is described using approximate mathematical models for a collector and a storage loop as given in Section 3. System design parameters are to be identified by a closed-loop equation which characterises system daily performance.
The uncertainty of identified parameters relates to

a. approximations used in the mathematical model

b. precise characterisation of energy status of a system under the test at the beginning and at the end of the daily measurement

Characterisation of energy status is the most delicate and essential point of the test procedure. Regarding to that particular point we refer two possible procedures:

1. laboratory testing

2. on-site testing

In laboratory testing, characterisation of energy status will, in general, not create difficulties.

Testing on-site is more delicate because any interruption of hot water supply to the consumers is to be avoided.

In both procedures this characterisation is performed by applying a reasonably high load flow rate to a system under the test. In that sence a uniform temerature in the solar part of the storage (i. e. excluding upper part of a storage where an electrical heater is situated.) can be achieved.

The test method is applicable to small scale (i.e. forced, thermosiphon and ICS systems) and large scale systems (i.e. with two or more storages connected in paralel and/or series).

Hence all these systems can be described by the similar mathematical model we will concentrate on the fundamental model considering basic solar water heater configuration.

3 Theoretical Model

A theoretical model is developed for a single tank domestic solar water heating system with forced/thermosiphon circulation and submerged or external heat exchanger (schematic diagram of the system with forced circulation and submerged heat exchanger is given in Fig 1).

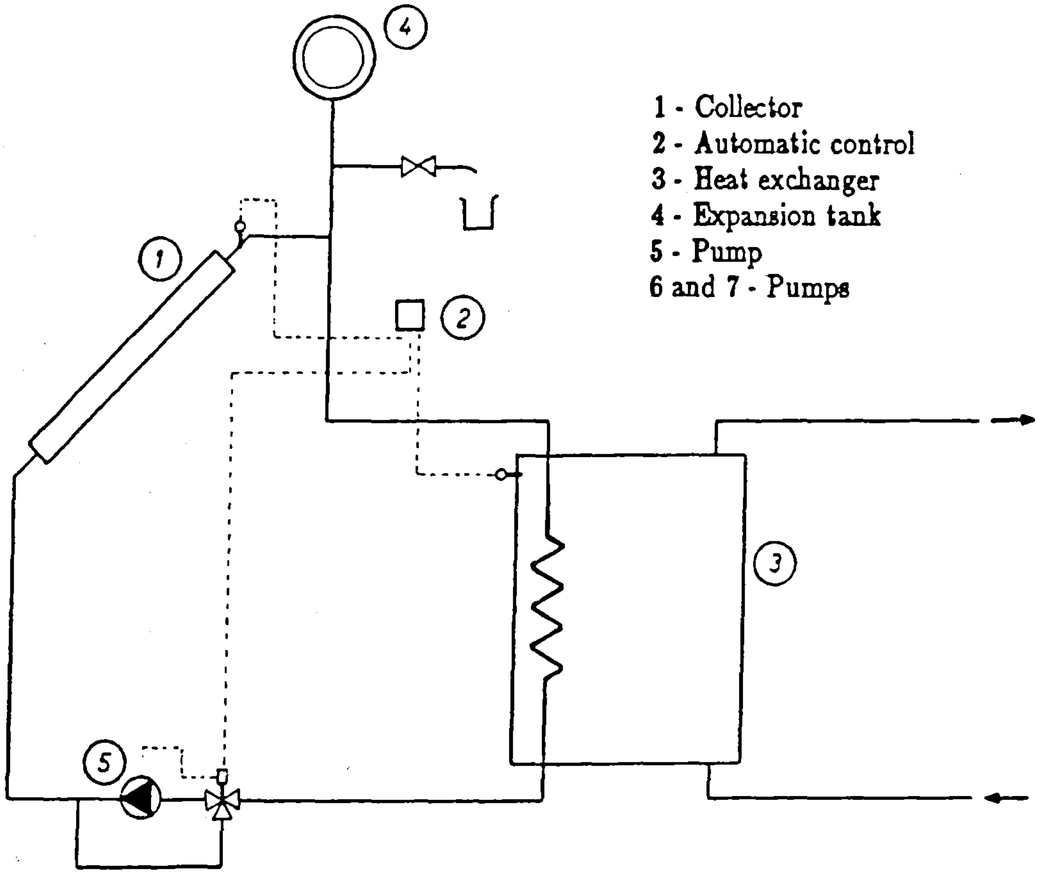

Figure 1: Solar Water Heater with Forced Circulation and Submerged Heat Exchanger

The basic approach used here seems to be sufficiently general so that the conclusions made for these configurations are valid for other conventional types of system configurations (forced circulation system with external heat exchanger,thermosiphon system without heat exchanger and integral collector storage (ICS) systems).

3.1 Collector Loop

The collector loop is described by a modified Hottel-Whillier- Bliss [6] equation:

$$\dot{Q}_c = AF_R[(\tau\alpha)G - U_L(T_{ci} - T_{ca})] \tag{1}$$

The heat removal factor includes the heat loss coefficient of pipes in the collector loop [7].

Optical efficiency of the collector loop can be approximated by a linear function of the diffuse part of solar irradiation:

$$(\tau\alpha) = (\tau\alpha)_{ob}(1 - f_d) + (\tau\alpha)_{od} f_d \tag{2}$$

An overall collector heat loss coefficient is approximated by a linear function of the average difference of temperatures: that of the mean collector temperature and of the ambient temperature;

$$U_L = U_{Lo} + \gamma \frac{\int_{op}(T_{cm} - T_{ca})dt}{d_{op}} \tag{3}$$

The effect of wind speed can also be taken into account by the assumption of linear dependence of heat loss coefficient on the wind speed on the collector surface [8]. Sufficiently accurate identification of both dependences would require a considerable amount of data. Since this work is concerned with developing a short-term testing procedure,we shall deal with temperature dependence only. For this it is necessary to keep the wind velocity on the collector surface constant (i.e. 3 - 5 m/s). This can be done artificially by means of fans.

The fundamental assumption made is that the effect of collector loop heat capacity could be neglected. Howewer, for intensively varying meteorological conditions there is still a possibility of taking into account a theoretical value of effective collector loop capacity.

3.2 Storage Loop

The physical characterisation of storage is more complex. In principle each tank configuration should be individually modelled from the multidimensional model by a momentum equation and the turbulence model. It is obvious that this type of sophisticated modelling could not be used for the development of a testing procedure. For the latter purpose it is necessary to develop a simplified model where the results of more sophisticated models can be generalised in a form easy for describing the relevant physical processes and enabling to quantify their effects by certain observable quantities. Another reason for developing such a model is the necessity that the model should be valid for a wide range of storage system configurations. The model defined in this work is one-dimensional.
The model takes into account:

(i) heat losses to the environment

(ii) thermal interaction of the storage with the collector loop (heat gain or extraction through directly connected inlet and outlet)

(iii) extraction of heat to the user

(iv) internal conduction and mixing effect between the layers (mixing is mainly caused by turbulence but also could be induced by thermal bridges and storage wall conduction)

The effect of mixing is modelled as a parallel heat transfer path and is quantified by a mixing conductivity in a thermal network. When there are no thermal bridges, it is reasonable to assume that the value of the mixing conductivity between the adjacent layers is the same. The mixing conductivity should in principle be determined from the measurements. Since the mixing intensity is a certain function of the load flow rate, it is assumed here that mixing conductivity is a first or second order function of load flow-rate.

The water replacement in the tank between the layers depends on the size of the tank, the location and geometry of fluid inlets, the fluid entrance velocity, etc. In this model the following pattern was assumed for the water replacement: the incoming water from the load loop replaces the water in the bottom layer of the tank, the water in this layer in its turn replaces the water of the layer above, and so on. Although the storage model is a specific one, the conclusions made for this model are valid for other types of storage configurations (other patterns of water replacement between the arbitrary numbers of layers and the positions of inlets and outlets).

The governing set of differential equations for storage with three horizontal layers for thermosiphon/forced circulation system with heat exchanger in the bottom layer is:

$$C_1 \frac{dT_{s1}}{dt} + k_1 A_s U_s (T_{s1} - T_{sp}) + (\dot{m}_d c + \lambda_m + \lambda_c)(T_{s1} - T_{s2}) = 0 \tag{4}$$

$$C_2 \frac{dT_{s2}}{dt} + k_2 A_s U_s (T_{s2} - T_{sp}) - \dot{m}_d c (T_{s3} - T_{s2}) - (\lambda_m + \lambda_c)(T_{s1} + T_{s3} - 2T_{s2}) = 0 \tag{5}$$

$$C_3 \frac{dT_{s3}}{dt} + k_3 A_s U_s (T_{s3} - T_{sp}) + \dot{m}_d c T_{s3} - (\lambda_m + \lambda_c)(T_{s2} - T_{s3}) - \epsilon \dot{m}_c c (T_{co} - T_b) = 0 \tag{6}$$

With abbreviations: $T_{s1} = T_o - T_r$; $T_{s2} = T_m - T_r$; $T_{s3} = T_b - T_r$; $T_{sp} = T_{sa} - T_r$.

k_1, k_2 and k_3 are constants representing the part of layer surface area in the total storage surface area:

$$k_i = \frac{A_i}{A_s}; \qquad i = 1\ 2, 3$$

An additional expression describing collector loop performance is:

$$\dot{m}_c c \epsilon (T_{co} - T_b) = (\tau\alpha) A F_R G - A F_R U_L (T_{ci} - T_{ca}) \tag{7}$$

or analogously:

$$\dot{m}_c c\epsilon(T_{co} - T_b) = (\tau\alpha)AF_m G - AF_m U_L(T_{cm} - T_{ca}) \tag{8}$$

If the collector heat capacity rate is lower than the demand heat capacity rate, and if the submerged heat exchanger is situated in the bottom layer, the heat exchanger effectiveness may be expressed by the equation:

$$\epsilon = \frac{T_{co} - T_{ci}}{T_{co} - T_b}$$

It should be emhasized that the set of differential equations is valid for an operating period ($T_{co} \geq T_{ci}$) only.

Let us express the governing set of differential equations for other common system configurations: forced system with/without external heat exchanger and thermosiphon system without heat exchanger. The same water replacement pattern as was taken above for the load loop has been applied for the collector loop. The system behaviour during operating time may then be described by the following set of differential equations:

$$C_1\frac{dT_{s1}}{dt}+k_1A_sU_s(T_{s1}-T_{sp})+(\dot{m}_dc+\lambda_m+\lambda_c)(T_{s1}-T_{s2})-\dot{m}_cc(T_{co}-T_r-T_{s1}) = 0 \tag{9}$$

$$C_2\frac{dT_{s2}}{dt} + k_2A_sU_s(T_{s2} - T_{sp}) - \dot{m}_cc(T_{s1} - T_{s2}) - \dot{m}_dc(T_{s3} - T_{s2}) - \\ - (\lambda_m + \lambda_c)(T_{s1} + T_{s3} - 2T_{s2}) = 0 \tag{10}$$

$$C_3\frac{dT_{s3}}{dt}+k_3A_sU_s(T_{s3}-T_{sp})+\dot{m}_dcT_{s3}-\dot{m}_cc(T_{s2}-T_{s3})-(\lambda_m+\lambda_c)(T_{s2}-T_{s3}) = 0 \tag{11}$$

An additional expression describing the collector loop performance is:

$$\dot{m}_c c(T_{co} - T_{ci}) = (\tau\alpha)AF_R G - AF_R U_L(T_{ci} - T_{ca}) \tag{12}$$

or

$$\dot{m}_c c(T_{co} - T_{ci}) = (\tau\alpha)AF_m G - AF_m U_L(T_{cm} - T_{ca}) \tag{13}$$

It should be emphasized that the heat removal factor F_R (or F_m) in these equations includes the heat exchanger effectiveness if a forced system with an external heat exchanger is considered.
These examples are only the special cases of storage tank configurations. Storage with a a desirable number of layers with or without heat exchanger and any position of inlets and outlets of collector and demand loop can be considered for forced/thermosiphon systems.

3.3 ICS System

An integrated collector storage system may be described in a similar way, by a single differential equation (valid only during the operating period).

$$C\frac{dT_s}{dt} + \dot{m}_d c T_s = (\tau\alpha)AF_m G - AF_m U_L(T_s - T_{ca}) \tag{14}$$

3.4 Overall System Performance

The sets of differential equations describe thermal networks by electrical analogies. Examples of the thermal networks for a forced system with an internal heat exchanger and an ICS system are given in Fig 2 and Fig 3. The water replacement pattern is simulated by electric current analogy. Conductivities between the nodes represent the internal water conductivity and mixing effect as already discussed. The conductivity $\dot{m}_d c$ represents the flow capacity rate of load loop.
The collector loop and storage perfomance are analysed jointly, as it should be, because of the feedback effect of the storage (degree of stratification) on the collector loop conversion efficiency. The feedback effect can be characterised by stratification parameter β, defined by the following modification of the Hottel-Whillier-Bliss equation:

$$Q_c = AF_R[(\tau\alpha)H_a - \beta U_L \int_{op} (T_o - T_r)dt] \tag{15}$$

where:

$$\beta = \frac{\int_{op}(T_{ci} - T_r)dt}{\int_{op}(T_o - T_r)dt} \tag{16}$$

$$H_a = H_g + \frac{U_L}{(\tau\alpha)}\vartheta_{ac} \tag{17}$$

$$H_g = \int_{op} Gdt \tag{18}$$

$$\vartheta_{ac} = \int_{op}(T_{ca} - T_r)dt \tag{19}$$

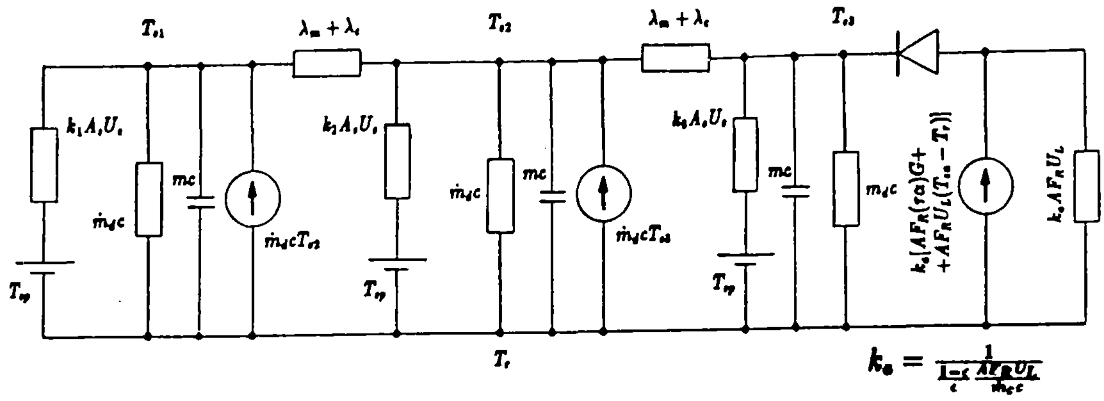

Figure 2: Thermal network for the forced system with an internal heat exchanger

It should be pointed out that this modification has its physical justification. Namely, H_a is the active energy potential of the system. This term fundamentally modifies the definition used by Kenna [9] and Stein [10] by integrating the energy potential over the operating period (i. e. the time of active solar conversion).

The physical meaning of such a definition is that it expresses the real energy potential available to the system with respect to

i)meteorological and operating conditions, and

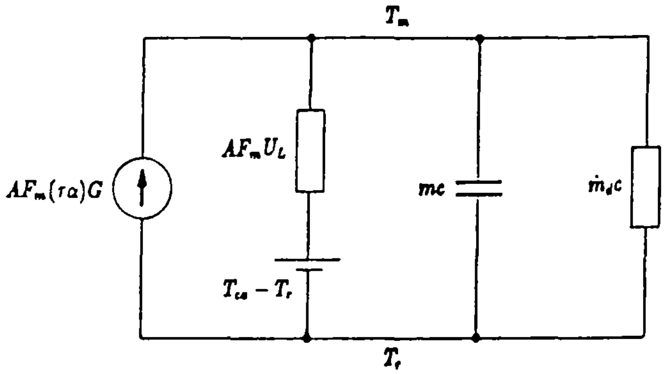

Figure 3: Thermal network for operating period of the ICS system

ii)carry-over energy.

The active energy potential could be zero even if a considerable irradiance is available, but when the energy contained in a storage disables the collector pump all over the day. If the conversion of solar energy takes place then the active energy potential is certainly positive.

The eqn (15) can not be used for thermosiphon systems because the variations of the collector flow-rate affect the heat removal factor. These variations will depend on meteorological conditions and on the design of the system; however, if a strongly varying collector flow-rate is to be expected it is necessary to rearrange eqn (15) by incorporating the collector efficiency factor, F'. The collector efficiency factor could be considered unaffected in a wide range of collector flow-rates for a majority of collector designs. Parameter F_m is aproximately the same as the collector efficiency factor and the eqn (15) can be presented in a slightly modified form:

$$Q_c = AF_m[(\tau\alpha)H_a - \beta_m U_L \int_{op} (T_o - T_r)dt] \qquad (20)$$

by a different definition of feedback parameter β_m :

$$\beta_m = \frac{\int_{op}(T_{cm} - T_r)dt}{\int_{op}(T_o - T_r)dt} \qquad (21)$$

By the common assumption that collector mean temperature, T_{cm} is the arithmetic mean temperature of the collector inlet and outlet temperature, we can write:

$$\beta_m = \frac{\beta + 1}{2} \tag{22}$$

The eqn (15) has a modified form by inserting the above substitution:

$$Q_c = AF_m[(\tau\alpha)H_a - \frac{\beta + 1}{2}U_L \int_{op} (T_o - T_r)dt] \tag{23}$$

Since the closed loop form has to contain the measurable quantities only (except parameters which are to be identified), let us express storage losses during operating period with respect to the temperature of the top layer. It is assumed here that this temperature is the same as the load exit temperature. By introducing a second stratification parameter, Ψ, we obtain:

$$Q_{lot} = \Psi A_s U_s \int_{op} (T_o - T_r)dt - A_s U_s \int_{op} (T_{sa} - T_r)dt \tag{24}$$

where

$$\Psi = k_1 + k_2 \frac{\int_{op}(T_m - T_r)dt}{\int_{op}(T_o - T_r)dt} + k_3 \frac{\int_{op}(T_{ci} - T_r)dt}{\int_{op}(T_o - T_r)dt} \tag{25}$$

With the stratification parameters defined above, the energy balance over operating period becomes as follows;

$$AF_R(\tau\alpha) \int_{op} Gdt + AF_R U_L \int_{op} (T_{ca} - T_r)dt =$$

$$= (\beta F_R U_L + \Psi A_s U_s + \dot{m}_d c) \int_{op} (T_o - T_r)dt + Q_{sop} - A_s U_s \int_{op} (T_{sa} - T_r)dt \tag{26}$$

Q_{sop} is the energy stored in the tank during operating period. It is assumed that the flow rate is constant during operating time, and that the relief valve need not to be activated during that time.
Combining (15) with (26) we obtain:

$$Q_c = F_R(\tau\alpha)H_a - k_o F_R[(\tau\alpha)H_a - Q_{sop} + A_s U_s \int_{op} (T_{sa} - T_r)dt] \qquad (27)$$

with the abbreviation:

$$k_o = \frac{\beta A F_R U_L}{\beta A F_R U_L + \Psi A_s U_s + \dot{m}_d c} \qquad (28)$$

The energy balance equation during operating period is defined by:

$$Q_{sol} + \Psi A_s U_s \int_{op} (T_o - T_r)dt + Q_{sop} = Q_c + A_s U_s \int_{op} (T_{sa} - T_r)dt \qquad (29)$$

or:

$$Q_{sol} = \frac{1}{1 + \frac{\Psi A_s U_s}{\dot{m}_d c}} [Q_c - Q_{sop} + A_s U_s \int_{op} (T_{sa} - T_r)dt] \qquad (30)$$

Combining (27) and (30) and by rearranging the terms we obtain:

$$Q_{sol} = \frac{\dot{m}_d c}{\dot{m}_d c + \beta A F_R U_L + \Psi A_s U_s} (A F_R(\tau\alpha)H_g + A F_R U_L \vartheta_{ac} + A_s U_s \vartheta_{sc} - Q_{sop}) \qquad (31)$$

or

$$Q_{sol} = \frac{\dot{m}_d c}{\dot{m}_d c + \beta_m A F_m U_L + \Psi A_s U_s} (A F_m(\tau\alpha)H_g + A F_m U_L \vartheta_{ac} + A_s U_s \vartheta_{sc} - Q_{sop}) \qquad (32)$$

where ϑ_{sc} is the integrated temperature difference:

$$\vartheta_{sc} = \int_{op} (T_{sa} - T_r)dt \qquad (33)$$

Parameter Ψ can be expressed as a function of β and k_i parameters.

If we assume that the storage temperature varies linearly with vertical direction along the height of the submerged heat exchanger (i.e. for the heat exchanger situated across the middle layer), then parameter Ψ can be presented as:

$$\Psi = \frac{(2k_1 + k_2)\beta + 2k_2 + k_3}{2} \tag{34}$$

If the inlets and outlets of the collector and load loop are situated at the top and bottom of the storage, and if coefficients k_1 are equal) then it can be approximated:

$$\Psi \approx \frac{\beta + 1}{2} \tag{35}$$

This approximation will not considerably influence the final result because it is always fulfilled:

$$\Psi A_s U_s << \dot{m}_d c + AF_R U_c$$

It should be noticed that the term representing heat losses (even if heat loss coefficient is extremely high) is one to two orders of magnitude minor with respect to other terms in the energy balance eqn (29) for the days with considerable daily irradiation so that these approximations are quite reasonable.
Analogously to the procedure for derivation of eqns (15) and (23), for a forced/thermosiphon system, we will derive the equivalent equation for ICS systems by using the thermal network presented in Fig 3. Expressing the energy balance during operating period, we get:

$$AF_m(\tau\alpha)H_g + AF_m U_L \vartheta_{ac} = (\dot{m}_d c + AF_m U_L)\vartheta_m + Q_{sop} \tag{36}$$

where:

$$\vartheta_m = \int_{op} (T_m - T_r)dt \tag{37}$$

Finally, we obtain:

$$Q_{sol} = \frac{\dot{m}_d c}{\dot{m}_d c + AF_m U_L}(AF_m(\tau\alpha)H_g + AF_m U_L \vartheta_{ac} - Q_{sop}) \tag{38}$$

3.5 Closed-Loop Form Models

It is obvious that eqns (31), (32) and (38) can be presented as linear functions of the parameters which are to be identified. This fact will make the identification procedure extremely simple [11]. It can be observed that parameter η (the effective conversion efficiency of collector loop over operating period) and T^* (effective value of reduced temperature constant over operating period) are described by measurable quantities only:

(i) forced circulation systems

$$\eta = F_R(\tau\alpha) - T_i^* F_R U_L \tag{39}$$

where η and T_i^* are:

$$\eta = \frac{Q_{sol} + Q_{sop} + \frac{Q_{sol} A_s U_s \Psi}{\dot{m}_d c} - \vartheta_{sc} A_s U_s}{A H_g} \tag{40}$$

and

$$T_i^* = \frac{\int_{op} (T_{ci} - T_{ca})\, dt}{H_g} \tag{41}$$

(ii) thermosiphon and forced circulation systems

$$\eta = F_m(\tau\alpha) - T_m^* F_m U_L \tag{42}$$

where η and T_m^* are:

$$\eta = \frac{Q_{sol} + Q_{sop} + \frac{Q_{sol} A_s U_s \Psi}{\dot{m}_d c} - \vartheta_{sc} A_s U_s}{A H_g} \tag{43}$$

$$T_m^* = \frac{\int_{op}(T_{cm} - T_{ca})dt}{H_g} \tag{44}$$

where

$$T_{cm} = \frac{(T_{ci} + T_{co})}{2} \tag{45}$$

(iii) ICS systems:

$$\eta = F_o(\tau\alpha) - T_o^* F_o U_L \tag{46}$$

where η and T_o^* are:

$$\eta = \frac{Q_{sol} + Q_{sop}}{AH_g} \tag{47}$$

and

$$T_o^* = \frac{\int_{op}(T_{co} - T_{ca})dt}{H_g} \tag{48}$$

In the following section the testing methodology is developed on the basis of these specially defined operating conditions and the closed loop mathematical model.

4 Testing Procedure

The aim of the proposed testing method is to identify the system parameters necessary for long term performance prediction.

The testing methodology may include 5 main parts:

1. Testing storage heat loss coefficient and storage heat capacity

2. Testing the complete unit in order to identify:

    - the collector loop heat loss coefficient
    - the optical efficiency of the collector loop
    - the storage model (mixing conductivity and/or the model characterised by the number of storage layers and their dimension)
    - the effective product of the average heat exchanger transfer coefficient and the heat transfer surface area (for storage with a submerged heat exchanger)
    - the dependence of optical efficiency on the part of diffuse irradiation (optional)
    - the temperature dependence of the heat loss coefficient (optional)

3. Estimation of the parameters :

    - the heat loss coefficient of the pipes (optional)
    - the collector incident angle modifier (optional)
    - for thermosiphon system only the pressure drop in collector loop (optional)

Separate tests for specific types of the system should be carried out as well:

4. Test to determine a storage model (mixing conductivity and/or a model characterised by the number of storage layers and their dimensions) for storage with auxiliary heater

5. Test of the control/regulation units

After the measurements of the collector area, storage heat capacity and storage heat loss coefficient (test of point 1) are carried out, the identification of parameters of point 2 is elucidated. It represents the basic part of the testing procedure. Testing the complete unit involves minimum of 5 one-day tests. An additional set of data is necessary to identify optional values listed in point 2.

Identification of the parameters listed in point 3. is optional. These parameters can be determined either by experimental procedures or can be theoretically estimated. Heat losses of the pipes can be estimated theoretically from the heat loss coefficient of the insulation given by the manufacturer.

The dependence of optical efficiency on the incidence angle of solar irradiance can be estimated by standard test methods like ASHRAE 93-77 [12] or theoretically estimated by absorber and glazings optical properties [7].

The pressure drop can be theoretically estimated by dividing the thermosiphon loop into a number of segments normal to the flow direction and applying Bernullis equation for incompressible flow to each segment [13].

Testing for point 4 is necessary to determine the mixing effect caused when the auxiliary heater is in operation. The description for the test of point 5 is already well elaborated and will not be considered here.

Tests for points 2 and 4 are described in more details in the next Sections.

4.1 Test on a Complete Unit

This test is the essental part of the test method and it encompasses a number of single-day measurements.
A single-day measurement consists of three main sequences:

Sequence A. Preconditioning: Bringing the solar part of the system at the uniform temperature

Sequence B. Monitoring the energy flows at the system during active conversion of solar energy

Sequence C. Measuring the carry-over energy in the system at the end of the day by bringing the system at the uniform temperature

Preconditioning is performed by circulating the water through a load loop. However, the heat capacity of a collector loop should be respected. The best results can be provided if the collectors are shielded and collector pump activated during the preconditioning. In this case, collector loop is brought at the approximately same temperature level as a solar part of the storage. Naturally, this can be performed when testing is carried out in laboratory. In other cases preconditioning should take place at the time the irradiance is not significant (i.e. $G < 200W/m^2$) to prevent an influence of collector thermal capacity.

The measurement of sequence B can start when a uniform temperature is reached in the solar part of the storage. This test is to be carried out mainly during an active conversion of solar energy.

If the test is performed in laboratory, that gives opportunity to apply such operating conditions which enable fast and the most accurate test results. That is why we select very artificial operating conditions for laboratory testing:

(i) continuous load flow rate

(ii) inlet storage temperature from the mains can be selected for daily measurement point

In selection of these conditions we assume that design parameters of a system under the test are independent on the operating conditions. Naturally, these operating conditions are unsuitable and even not possible for on-site measurement. There, a consumer behaviour dictates the draw-off pattern and therefore natural oprating conditions apply.

The test ends (sequence C) by measurement of heat content of the storage at the end of the day. It is again performed by circulating the fluid through load loop as the system preconditioning.

Since we are primarily interested in precisely characterising the system behaviour for the days with considerable energy potential, we recommend carrying out test for the days with minimum irradiation during operating period of $9MJ/m^2$ with the diffuse part of irradiation not higher than

Experimental Variable	Precision	Accuracy
Local Time	± 0.01 h	± 0.01 h
Surrounding Air Speed	± 0.5 m/s	± 1 m/s
Ambient Air Temperature	± 0.1 K	± 0.1 K
Fluid Temperature	± 0.05 K	± 0.05 K
Temperature Difference	± 0.05 K	± 0.05 K
Flow-Rate	± 1 %	± 1 %
Auxiliary Energy	± 2 %	± 2 %

Table 1: Measurement accuracy and precision

40% . Because of the possible influence of an incident angle modifier, we recommend that the daily test be taken symmetrically over the solar noon, if possible.

The average value of air speed should be in the range 0 - 2 m/s (or 3 - 5 m/s if more site-specific) on the collector plane during the measurement in order to reduce data scattering due to the wind effect. The accuracy required for measurement equipment and sensors is given in Tab 1.

In order to increase the accuracy of test results, one of the criteria followed up in selecting data points should be that the minimum reduced temperature constant should correspond to $\eta \approx F_R(\tau\alpha)$ and that its maximum value should correspond to $\eta < F_R(\tau\alpha)/2$. A further criterion for selecting both the quantity of test data and the necessary range of reduced temperature constants can be that the relative standard deviation of identified parameters should not exceed:
±3% for optical efficiency and
±10% for the collector heat loss coefficient.

If these limits are exceeded than it is necessary to identify the dependence of optical efficiency on the part of diffuse irradiation and the temperature dependence of a collector heat loss coefficient by an additional test. This additional test can be provided by measurements on days with a higher percentage of diffuse irradiation (i.e. in the range of 50 - 80 %) and for a range of temperature differences between the collector mean temperatures and the ambient temperature.

In the next Sections we describe the procedure for laboratory and on-site testing of small scale (i.e. solar domestic hot water/SDWH systems) and large scale systems.

4.1.1 Laboratory Testing of SDHW Systems

Laboratory testing gives high flexibility in possibilities of selecting the measurements points necessary for identification procedure.

Namely, values of reduced temperature constant, and therefore efficiency, can be easily selected by choosing an appropriate reference temperature and/or load flow rate.

Preconditioning of the system is performed by the following operations:

(i) - controller (if any) is disabled and auxiliary heater turned off

(ii) - continuous flow-rate is applied with an appropriately chosen reference temperature in order to bring the system to a uniform temperature.

The system may be considered to have reached a uniform temperature if the difference in the temperatures at storage load exit and that at the inlet is less than 0.5 K. During preconditioning, the collector is shielded and the collector pump, if present, turned on manually. The test starts by removing the collector shield if the following conditions are fulfilled:

(i) - minimum irradiance, G_{min}, on collector plane (it is taken that $U_L/(\tau\alpha)$ is equal 20 W/Km^2 to be worthwhile even for the worst collectors) should be considerably higher than the threshold irradiation level:

$$G_{min} \geq 20(T_{ci} - T_{ca})$$

(ii) - and the incident angle, θ, should be:

$$\theta \leq 35^o$$

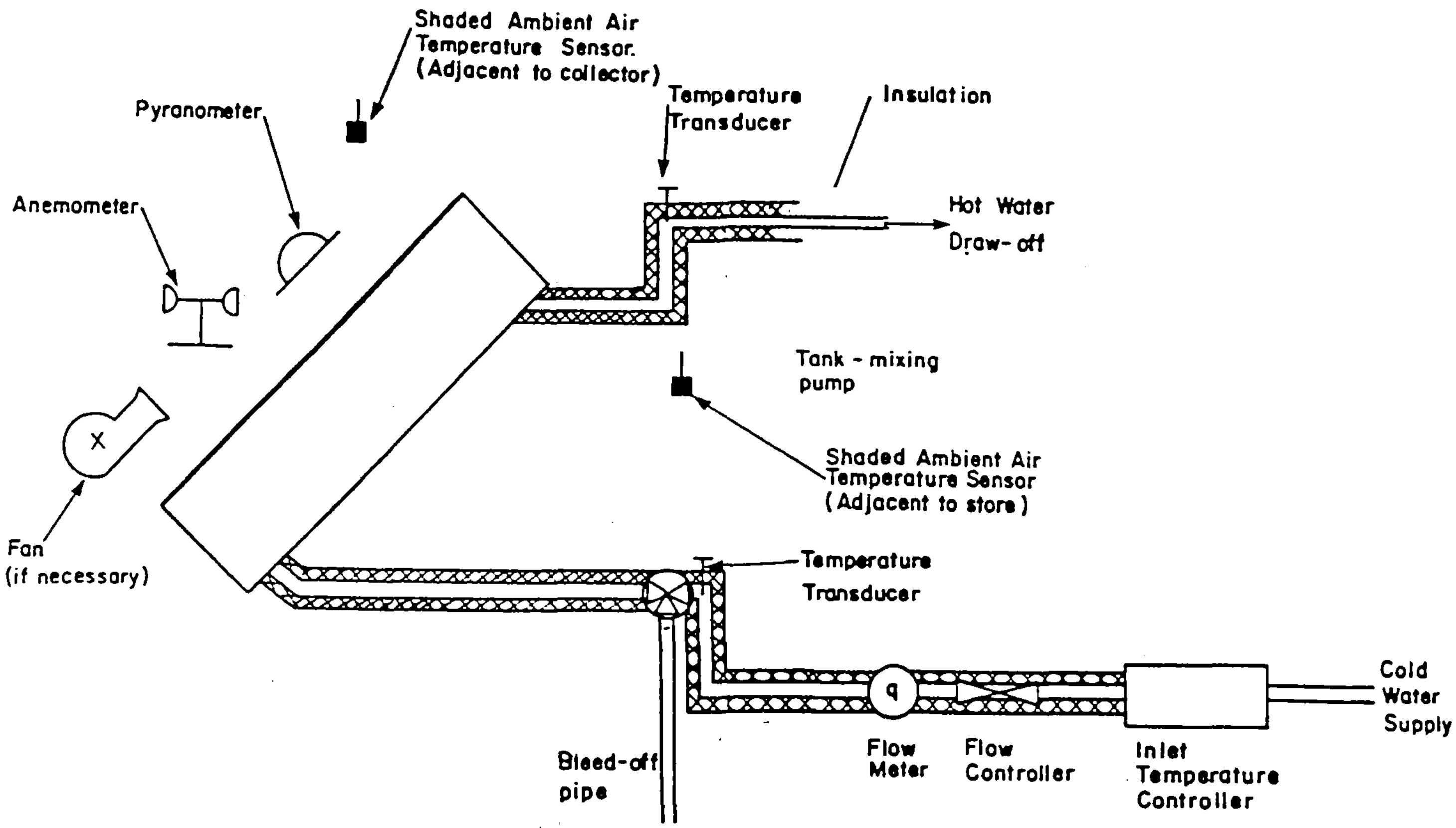

Figure 4: Test Loop for the ICS systems

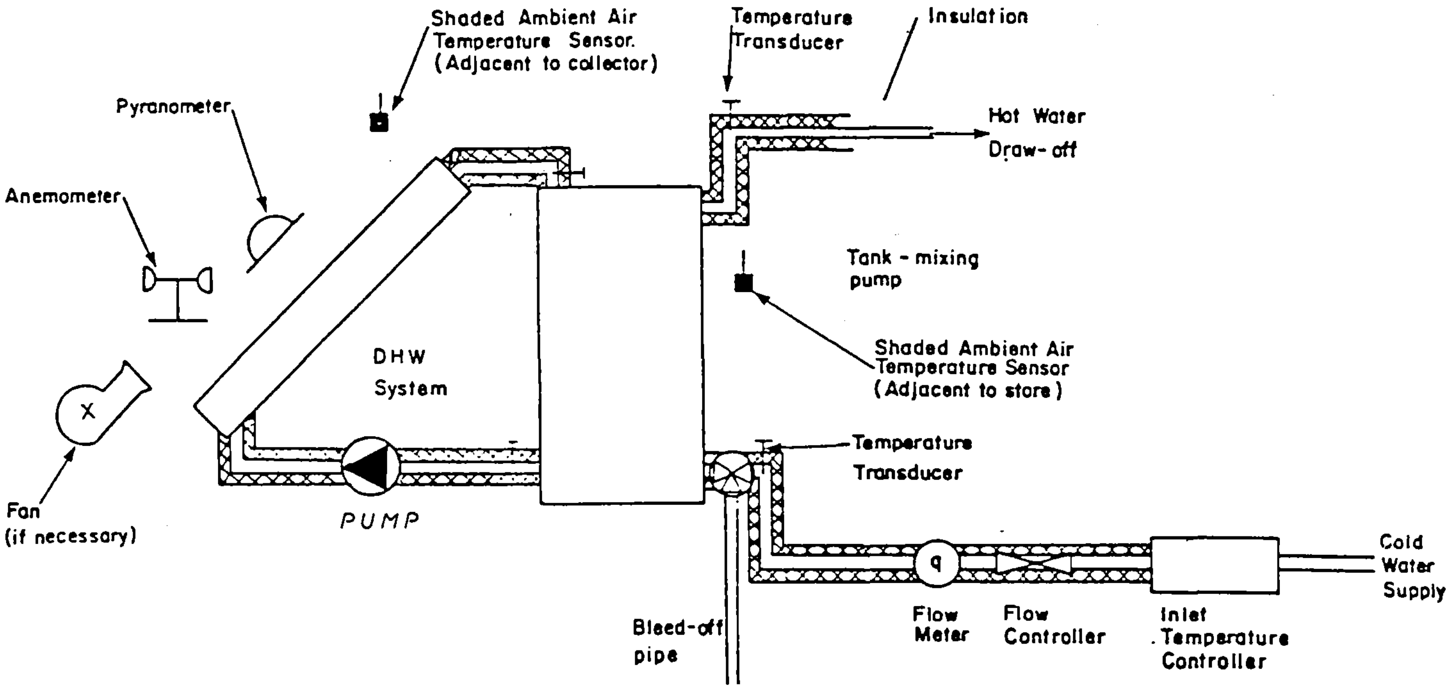

Figure 5: Test Loop for the Forced/Thermosiphon systems

By this moment, an active conversion takes part. The continuous load flow rate is applied all over the test. Measurements should be carried out for a range of demand flow-rates (i.e. 4 - 6 l/min, 9-11 l/min and 13-16 l/min) in order to enable quantifying the mixing effect into the storage.

This part of the test is accomplished by shielding the collector aperture area. However, this part of the test is to be terminated if one of the following conditions occurs:

(i) the temperature difference in the collector loop (or demand loop if ICS system is being tested) is less than 1K

(ii) the incident angle is higher than 35 degrees.

After shielding the collectors the demand flow-rate must be continued in order to measure the energy stored into the storage. The collector pump, if present, should be turned off 10 minutes after shielding the collectors. The reason is to reduce the influence of the collector loop thermal capacity.

The sequence C of the test is completed at the moment when the difference of the temperature at the load exit and that at the inlet of the storage is less than 0.5 K.

The energy stored into the storage can be measured by drawing off the storage water through the bleed-off pipe as well. The first measurement procedure can be recommended because it takes into account the effect of heat capacity of both the collector loop and the storage structure itself (i.e. storage without water). It should be noticed that if the final status of the storage differs from its initial status then it should be made correction to the eqns (40), (43) and (47) by adding in the nominators the following approximate term representing energy difference in the storage:

$$\Delta Q = \frac{m_s c}{2}[T_0(t_3) - T_0(t_1)]$$

A test loops for laboratory testing the ICS systems and forced or thermosiphon systems are shown in Figs 4 and 5. The flow controller should be capable of maintaining the flow-rate through the storage vessel at 1 % relative stability. The temperature regulator should be able to control the inlet fluid temperature within 0.2 K.

SDHW System with Heat Exchanger If the storage with a submerged heat exchanger is tested, it can be reasonably assumed that under the operational conditions applied in this test, the storage behaves as a countercurrent heat exchanger. Hence, the heat exchanger theory can be applied . In order to identify the heat exchanger effectiveness the temperatures at both inlets and outlets of the storage are to be measured in quasi steady state conditions. A quasi steady state condition is assumed to be reached if these temperatures do not vary more than 0.2 K within 15 minutes.

Additional Test for Storage with an Internal Heater The aim of this test is to quantify the mixing effect of the storage if the internal heater is in operation. That means we characterise the storage with an internal heater by two models: with and without internal heater activated.

The preconditioning procedure is similar to that described in section 4.1.1. After the system has reached a uniform temperature, the collector shield is removed, the demand flow-rate is stopped and the measurement can start. The system must operate from this point on as it is recommended by the manufacturer (i.e. for a system with immersed heater, the heater should be turned on by the controller immediately after the test has been started). The test should last at least four separate days each with the same initial temperature in the storage but with different demand flow-rates each day. It is recommended to apply the following withdrawal pattern: 4-6 l/min, 9-11 l/min and 13-16 l/min. from 11 a.m. to 1 p.m. each day. The daily irradiation must exceed 12 MJ/m^2.

The measurements of the electrical energy supplied to the heater should be carried out and the following energy flows: the heat extracted from the storage during the draw-off period and the carry-over energy in the storage the following morning. These experimental data along with previously identified values are to be used for determining the mixing conductivity (as a function of load flow rate) and/or the storage model defined by the number of layers and their dimensions.

4.1.2 On-Site Testing of SDHW Systems

On-site testing is restrictive in comparison with laboratory testing. Here, various values of reduced temperature constant might be more difficult to get, specially if similar weather conditions take part. Therefore, this test procedure can be time consuming regarding the laboratory testing.

Preconditioning is performed early in the morning ($G < 200W/m^2$) in order to eliminate collector loop heat capacity. It is carried out by circulating water through a load loop. It is suggested that withdrawal flow rate is in the range higher than 1.5 storage volume per hour. In that sence, the solar part of the storage can be assumed at uniform, cold water temperature, after approximately one hour.
At that moment sequence B of daily test can start.
It is pointed out that active energy potential is integrated over the time beginning at the moment collector pump is activated till the moment the pump is finally disabled. The priority in data analysis should be given to the days when collector pump was operating continuously all over the day or if the intervals the pump was not in operation during the day were less than 5 minutes duration each.

In opposite to the laboratory testing, here we identify only one mixing conducivity, that which characterises storage operation with an electrical heater activated.

It is recommended to end the test at the approximately same irradiance level as it was started in order to avoid the influence of collector loop thermal capacity (that holds if collector pump is in operation at that time or for thermosiphon systems).

The measurement of carry-over energy into the storage is performed by circulating the fluid through the load loop at the same flow rate as it was during preconditioning.

In Fig 6 the position of the sensors are presented.

SDHW Systems with Heat Exchanger The method used for measurement of heat exchanger effectiveness requires steady-state conditions during approximately one hour. Therefore, this kind of test is to be carried out applying continuous load flow rate at the time periods consumer does not require energy. The procedure is equivalent as that described in the previous section.

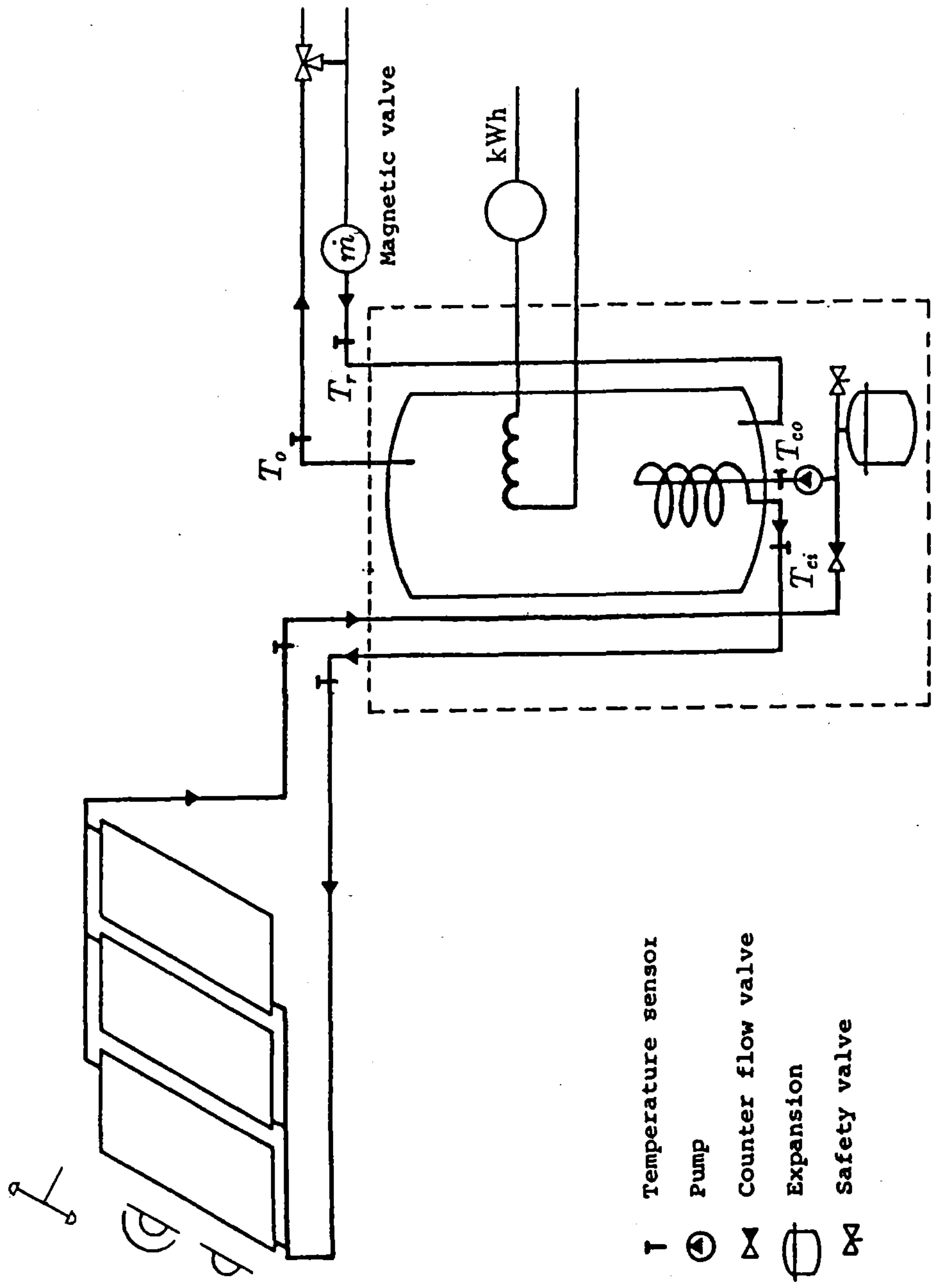

Figure 6: An Example of On-Site Measurement of SDHW System and the Positions of the Sensors

4.1.3 On-Site Testing of Large Systems

Large systems typically operates in various modes of operation over the day and therefore the test procedure should be somewhat different and more specific.

The main goal of test procedure remains in identification of system design parameters like

- collector loop optical efficiency
- collector loop heat loss coefficient
- equivalent mixing conductivity of each storage tank

Basic approach is to test system in several steps, in each step enabling only one mode of operation. Therefore, each test in principle represents the test described in Section 4.1.2.

In that sence, identification of the storage parameters can be conducted subsequently. In each sequence, a particular storage tank mixing conductivity is to be identified.

A test should start with controlling the automatic regulation unit. Thereafter, this unit is disconected and we manually enable a particular mode of system operation over a certain period of time which is necessary for identification of a particular storage mixing conductivity. After that, another mode of system operation is enabled and other mixing conductivity found.

For example, if system with two storages connected in paralel as shown in Fig 7 is considered, then the first sequence of measurement will take part by only one storage connected in the solar loop and the second measurement sequence deals with other storage connected only.

If a system consists of two storages connected in series, at first, we measure only one storage coupled to collector loop, and secondly, by both storages connected. By the first step we identify one mixing conductivity and another by the second step.

In other details, the procedure is similar to that described in Section 4.1.2.

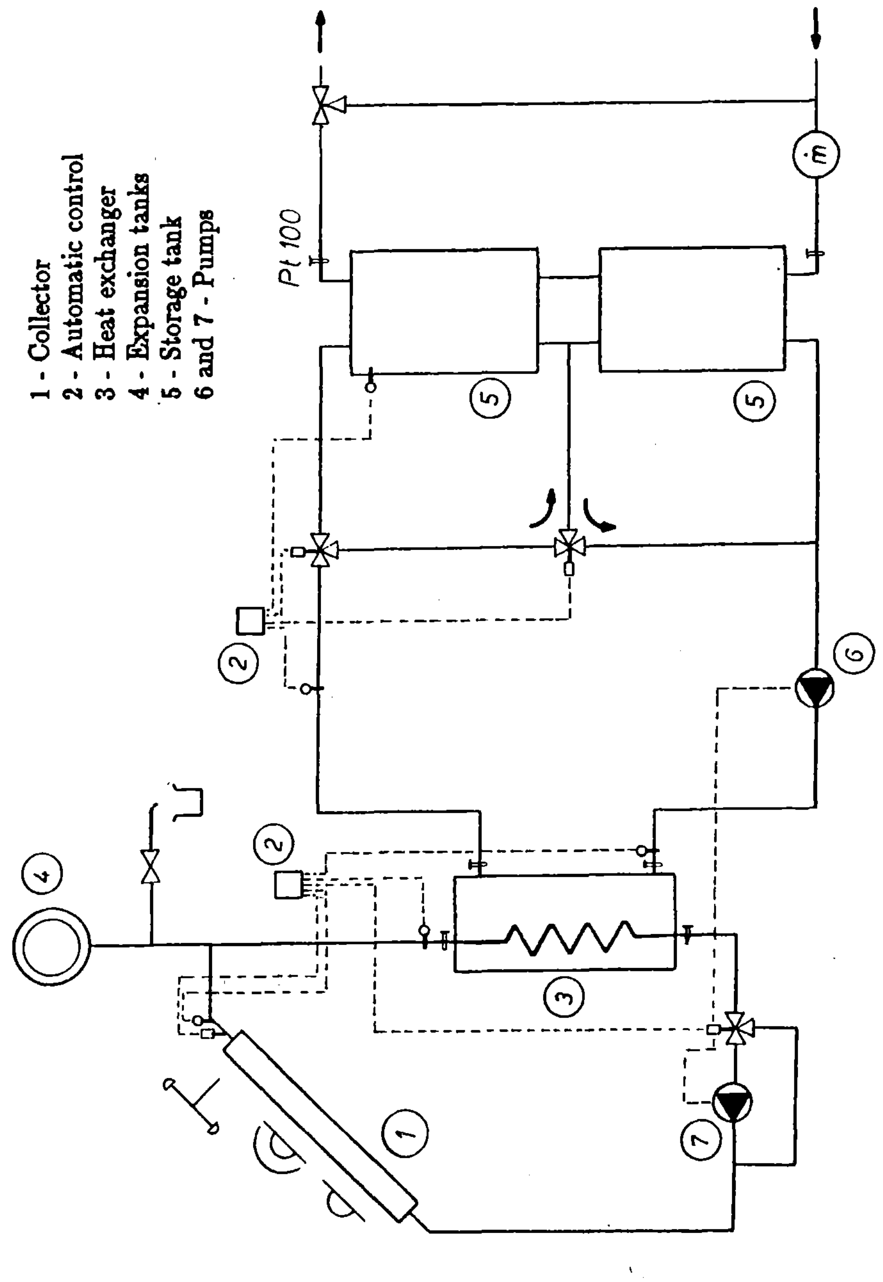

Figure 7: An Example of On-Site Measurement of a Large System and the Positions of the Sensors

4.2 Parameters Identification

Parameters identification considers two consequtive parts:

1. Identification of collector design parameters

2. Identification of mixing conductivity of the storage or the storage model

The second part relies on the measurements result but also on the identified parameters from the first part.

Identification is slightly different for laboratory and on-site measurements.

4.2.1 Laboratory Testing

Using the model developed in section 3. the collector loop parameters may be identified by the least square fitting method. The closed loop mathematical models for identification of the parameters are given by eqns (39), (42) and (46). The parameters to be identified are the optical efficiency of the collector loop and the heat loss coefficient of the collector loop.

After these values have been identified, the averaged collector loop flow capacity rate for forced/thermosiphon systems should be determined using the equation:

$$\dot{m}_c c = \frac{AF_R(\tau\alpha)H_g - AF_R U_L \int_{op}(T_{ci} - T_{ca})dt}{\int_{op}(T_{co} - T_{ci})dt} \tag{49}$$

Naturally, an equivalent equation can be used with F_m instead of F_R, and T_{cm} instead of T_{ci} in the nominator.

If the extension of test 2 in section 4.1.1. has been applied, the identification should be carried out by the eqn (39), (42) or (46) using substitutions given by eqns (2) and (3).

In this sense, the parameters $F_R(\tau\alpha)_{ob}$, $F_R(\tau\alpha)_{od}$, $F_R U_L$ and $F_R\gamma$ or the parameters $F_m(\tau\alpha)_{ob}$, $F_m(\tau\alpha_{od}$, $F_m U_L$ and $F_m\gamma$ are to be identified.

If system with an internal heat exchanger has been tested, the identification of the effective product of average overall heat transfer coefficient and heat transfer surface area can be performed by the measured values of heat exchanger effectiveness by well known relationship (see for example [14] for $\dot{m}_c c_c < \dot{m}_d c$:

$$(UA)_{exc} = \frac{ln(1 - \frac{1-\epsilon\frac{\dot{m}_c c_c}{\dot{m}_d c}}{1-\epsilon})}{1 - \frac{\dot{m}_c c_c}{\dot{m}_d c}} \dot{m}_c c_c \tag{50}$$

The set of data obtained in previous tests is used in order to determine a storage model. The above identified parameters, the operating conditions during the test (demand flow-rate) and the meteorological parameters (irradiance profile, ambient temperature) are the input parameters for identifying the mixing effect into the storage. We shall consider two possibilities for the characterisation of the mixing effect. The first approach considers the model described in section 3.: the mixing conductivity is to be identified as a function of the load flow-rate. Namely, for each test day the best fit of mixing conductivity can be determined by the trial and error method using the set of differential eqns (4) - (6). These mixing conductivities paired by corresponding demand flow-rates enable identification of functional dependence:

$$\lambda_m = f(\dot{m}_d c)$$

The ability to identify this functional dependence makes the model described in section 3. more flexible in comparison with the widely-used, one-dimensional storage models with fixed number of layers ignoring this dependence.
The second approach is to identify the storage model by adjusting the number of layers and their dimensions which gives the best fit to the daily measurement values. Predictions are to be made by the trial and error method by using various numbers of layers with different dimensions with the heat loss distribution corresponding to each storage layer area.

Both models are considered valid if they predict the data within the uncertainty band of measurements.

From the standpoint of standard procedure requirements, identification of the storage model by adjusting the number of layers and their dimensions may be preferable because most presently available computer programs use this model.

In the case where an internal heater is applied, the storage model has to be identified by a similar procedure but with the input data with electrical heater activated.

4.2.2 On-Site Testing

The collector parameters are to be identified by the equation (39), (41) and modified equation (40):

$$\eta^* = \frac{Q_{sol} + Q_{sop} - Q_e + A_e U_e (T_{set} - \overline{T}_{sa}) d + A_s U_s (\overline{T}_s - \overline{T}_{sa}) d + \Delta Q}{A H_g} \quad (51)$$

where

Q_e is electrical energy spent by an electrical heater during the B and C sequences (active conversion and carry-over measurement) of the test

d is time interval from the moment preconditioning is completed to the moment when carry-over energy measurment is over (B & C sequence)

$\overline{T}_s$ is a mean fluid temperature in the solar part of the storage given by the approximate equation:

$$\overline{T}_s = \frac{Q_{sol} + Q_{sop} - Q_e}{Vc} + T_r$$

where V is a total volume drawn off from the storage during the time d.

If extension of the test described in Section 4. is carried out then analogous equation for optical efficiency and heat loss coefficient dependences are to be applied.

After that the procedure is analogous to that described in previous section.

5 Experimental Results

Experimental investigation was carried out on a single tank indirect system subjected to normal outdoor meteorological conditions and specifically defined operating conditions defined by the test method. The system consisted of two solar collectors connected in parallel, a water storage tank with (a wrap around) heat exchanger, an on-off differential temperature controller, and a pump. A single-glass-cover, flat-plate collector was used. Each collector had an aperture area of 1.75 m^2. A double wall heat exchanger jacket surrounding the water tank allowed the heat transfer fluid to heat the water within the tank. The heat exchanger jacket was attached to the surface by mechanical bonding. The heat transfer fluid was normal potable water. The system was tested at the Faculty of Electrical and Mechanical Engineering in Split, Yugoslavia. The SDHW system was extensively instrumented. The calibrated (and paired for measurements of temperature differences) Pt-100 thermometers monitored the collector loop inlet and outlet temperature, the inlet and exit potable water temperatures and the temperature differences during hot water withdrawal. The quantity of water supplied to the load was measured by a ring-piston flow-meter. Meteorological information, recorded during the outdoor tests, included global and diffuse solar radiation on tilted surface, wind speed and ambient temperature.

The procedure applied can be described as follows:

Step 1. Measuring collector aperture area and storage volume

$$A = 3.5m^2$$

$$m_s = 260l$$

Step 2. Test of the storage heat loss coefficient:

The test loop shown in Fig 5 was used for this test. The continuous withdrawal during the night was applied with the inlet temperature of $50^oC, 60^oC$ and 80^oC. The collector loop was disconnected during the measurement. The overall heat loss coefficient was determined both by integrating the temperature difference between storage inlet and outlet temperature, and by measurement of the temperature difference in steady state conditions.

DATE	η	$T^* * 10^{-3}$	T_r	T_a	f_d	H_g	$\dot{m}_d$	v
1988		Km^2/W	°C	°C	%	Wh/m^2	kg/s	m/s
June 03	0.651	2.29	15.5	21.8	35	3923	0.167	1.2
June 07	0.620	2.99	15.5	22.0	20	3509	0.136	1.0
June 08	0.653	2.45	16.0	22.0	23	3446	0.063	1.6
June 09	0.691	-3.92	15.1	22.5	22	3974	0.223	1.7
June 14	0.620	10.29	30.7	25.0	35	3971	0.116	1.2
June 15	0.612	10.26	30.8	25.3	27	4264	0.098	1.3
June 16	0.678	1.12	22.1	25.0	22	3809	0.111	1.5
June 17	0.475	28.46	48.7	24.3	29	3212	0.088	1.3
June 21	0.392	39.27	58.5	25.2	31	3307	0.106	1.2
June 23	0.328	49.53	68.3	25.8	26	3356	0.106	1.2
June 27	0.559	20.34	39.1	23.7	37	3469	0.097	1.0
June 28	0.448	36.33	51.1	25.8	39	2427	0.105	0.9

Table 2: Test Results by [15] and [16]

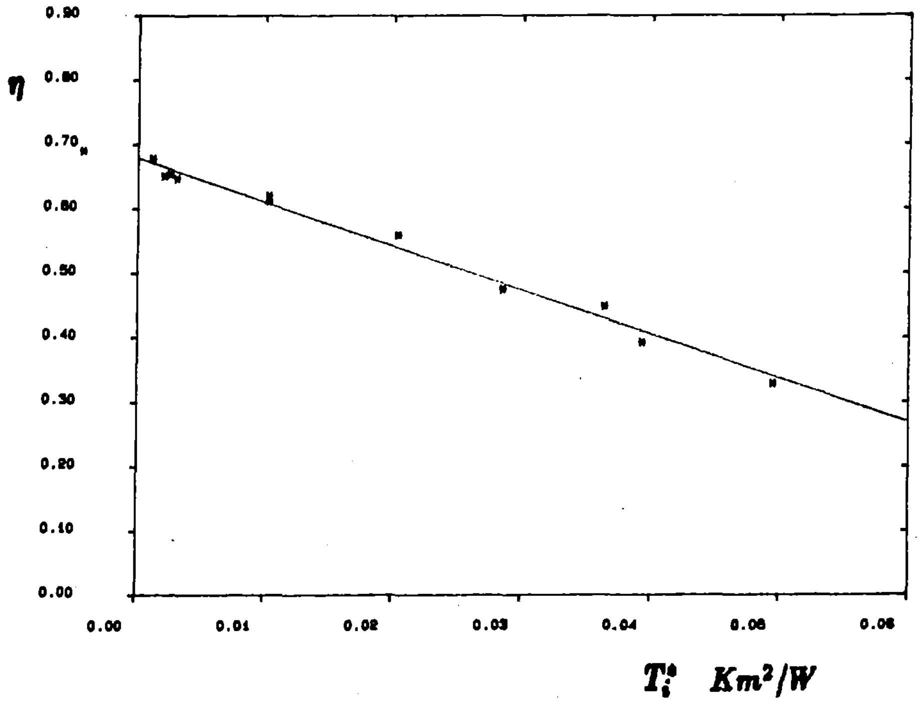

Figure 8: Graphical presentation of the test results

It was was identified:

$A_s U_s = 8W/K$

with root mean square error

$RMS_{A_s U_s} = 1.1W/K$

Step 3. Collecting of daily data as stated in section 4.1. The data are listed in Tab. 2. The graphical presentation of measurements data is given in Fig 8.

Step 4. Using eqn (39) and well known tools for linear statistical analysis, the following values were identified with 0.993 coefficient of correlation:

$F_R(\tau\alpha) = 0.676$ $\qquad$ $\mathrm{RMS}_{F_R(\tau\alpha)} = 0.006$

and

$F_R U_L = 6.8\frac{W}{Km^2}$ $\qquad$ $RMS_{F_R U_L} = 0.24\frac{W}{Km^2}$

As the relative standard deviations of both parameters are in acceptable range, it is worthless to identify the temperature dependence of heat loss coefficient and the dependence of optical efficiency on diffuse irradiation.

Step 5. The collector loop flow capacity rate was identified by eqn (49) for several daily measurements. The averaged value was:

$\dot{m}_c c = 157W/K$ $\qquad$ $RMS_{\dot{m}_c c} = 7W/K$

Step 6. The identification of the effective product of average overall heat transfer coefficient and the heat transfer surface area was performed by the measured values of heat exchanger effectiveness. Product of AU_{exc} was computed by eqn (50) for single measurement. The average values with root mean square error were:

$$(AU)_{exc} = 325W/K \qquad RMS_{AU_{exc}} = 28W/K$$

Step 7. Using the set of differential equations similar to eqns (4)-(6) along with the identified parameters and the meteorological data for each test day, the following dependence has been identified:

$$\lambda_m = 0.8\dot{m}_d c \qquad (c = 4,186\frac{kJ}{Kkg})$$

Step 8. Using the simulation program developed at FEM (based on the thermal network shown in Fig 2) we predicted solar savings of the system for the worst case limits of the identified parameters combination:

case I: $F_R U_L = 6.83 + RMS_{F_R U_L}$ $F_R(\tau\alpha) = 0.676 - RMS_{F_R(\tau\alpha)}$

and

case II: $F_R U_L = 6.83 - RMS_{F_R U_L}$ $F_R(\tau\alpha) = 0.676 + RMS_{F_R(\tau\alpha)}$

In order to calculate the deviations in solar savings caused by the deviations in identified design parameters simulation was carried out for Split meteorological conditions using daily meteorological data for year 1981. The draw-off profile pattern used for simulation is shown in Tab 3 with the other parameters listed.

Set temperature .... **45 °C**
Mains temperature .... **15 °C**
Temperature in vicinity of the storage .... **20 °C**
Draw-off volume .... **300 l**
DRAW-OFF PATTERN:

HOUR	7-8	12-13	13-14	18-19	19-20	20-21
VOLUME	50l	50l	50l	50l	50l	50l

Table 2: Daily draw-off pattern and operational conditions

MONTH	H*	dev	Fnet case II	Fnet case I
			%	%
JAN	0.9	0.6	31.6	30.5
FEB	1.3	0.8	45.3	43.7
MAR	1.5	1.0	51.1	49.7
APR	1.8	0.7	57.2	55.1
MAY	2.2	0.5	67.5	65.0
JUN	2.4	0.5	74.6	72.2
JUL	2.5	0.6	76.4	74.2
AUG	2.4	0.6	75.2	73.0
SEP	2.5	0.5	78.7	76.8
OCT	2.1	0.6	70.5	68.5
NOV	1.4	0.6	48.3	46.7
DEC	1.1	0.7	41.2	39.9
YEAR	1.8	0.9	59.9	58.0

Table 3: Simulation results of the system performance for the worst case combination of test results for Mediterranean climate (Split); H^*- energy potential normalised with the heat required,*dev*- deviations of that potential over the month,*Fnet*- solar fraction

6 Conclusion

The test method presented here can be used for already installed or for outdoor/indoor laboratory testing of small-scale solar water heaters. It seems that the basic principle of the method to identify the system design parameters meets the majority of the requirements listed in the introduction. The major contribution of this method is that it offers a means of using site-specific meteorological data along with the system's design parameters. The first part of the method in fact presents the extended method for collector testing. Presentation of the collector efficiency as a function of reduced temperature constant is retained for the collector loop. The same set of data is used for identification of the mixing effect into the storage tank.

The method does not require costly loop infrastructure.

The identification of system design parameters is carried out by simple and widely accepted statistics procedures.

The method is flexible enough to be adapted to various system designs and storage types. The user is free to select the number of the parameters to be identified.

The proposed test method has entered International Standard Organization (ISO) documents by the decision of ISO TS 180 TC4 Committee Meeting in Berlin in October 1987 as one of the proposals to be considered for the international test standard.

7 Acknowledgments

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8 Nomenclature

A_i - storage sectional area, m^2
A - collector aperture area, m^2
A_s - storage area, m^2
c - specific heat of water, $kJ/(Kkg)$
C_1, C_2, C_3 - heat capacity of storage layers from top to the bottom, kJ/K
d_{op} - duration of the operation period, s
f_d - diffuse part of daily global irradiation
F' - collector efficiency factor
F_m - heat removal factor regarding mean collector temperature
F_R - heat removal factor regarding inlet collector temperature
F_o - heat removal factor regarding outlet collector temperature
G - irradiance, W/m^2
H_a - active energy potential, kJ/m^2
H_g - daily iradiation, kJ/m^2
$\dot{m}_c$ - collector loop flow rate, kg/s
mc - storage heat capacity, kJ/K
$\dot{m}_d$ - demand loop flow rate, kg/s
Q_c - heat gained by collector loop, kJ
Q_{los} - heat loss of the storage, kJ
Q_{sol} - heat extracted from the storage, kJ
Q_{sop} - heat stored in the storage during operating period, kJ
op - operating period, s
T_b - fluid temperature of the storage bottom layer, ^oC
T_{ca} - collector ambient temperature, ^oC
T_{ci} - collector loop inlet temperature, ^oC
T_{cm} - collector mean fluid temperature¡ ^oC
T_{co} - collector loop outlet temperature, ^oC
T_m - temperature of the water in ICS system, ^oC
T_o - temperature of the storage top layer, ^oC
$T_o(t_1), T_o(t_3)$-storage outlet temperatures at the test starting and stopping point,^oC
T_r - reference (mains) temperature¡ ^oC
T_s - fluid temperature of well-mixed storage (and ICS system)¡ ^OC
T_{sa} - storage ambient temperature, ^oC

U_L - overall loss coefficient of the collector, $W/(Km^2)$
U_{co} - parameter to be indentified, $W/(Km^2$
U_s - storage heat-loss coefficient, $W/(Km^2)$
Ψ - stratification parameter
β - stratification parameter
β_m - stratification parameter
γ - parameter characterising temperature dependence of collector heat-loss coefficient (to be indentified)
ΔQ - energy difference in the storage regarding test starting and stopping moment
ϵ - heat exchanger effectiveness
θ - incident angle, ^{o}
$(\tau\alpha)$ - optical effiency of collector loop including incident angle modifier
η_{ob}, η_{od} - parameters to be indentified
λ_c - conductivity of water layer, W/K
λ_m - mixing conductivity, W/K

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